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# RESEARCH ON THE INTENSITY DISTRIBUTION OF VERY LIGHT PARTICLES REFLECTED FROM A SOLID SURFACE OF CUBIC LATTICE STRUCTURE

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# RESEARCH ON THE INTENSITY DISTRIBUTION OF VERY LIGHT PARTICLES REFLECTED FROM A SOLID SURFACE OF CUBIC LATTICE STRUCTURE



A. Nikuradse

The following five reports should contribute to the clarification of the energy and impulse exchange between rarefied gases and solid surfaces. Therefore, they provide at the same time a contribution which increases our understanding of flow phenomena and heat transfer between a space vehicle and upper atmospheric levels.

## I. EXPERIMENTS

### Experimental Findings

1. The logarithmic decrement (attenuation resistance) of an oscillating disk depends on the kind of gas.

Figure 1

2. The spatial intensity distribution of reflected molecular jets is dependent on:

(a) the type of reflective solid surface.

Figure 2a

Some metallic and dielectric solid surfaces have different distribution curves; they show a pronounced forward reflection;

(b) the temperature of the reflective solid surface,

Figure 2b/2b[1].

The distribution curve shows a pronounced forward reflection in both cases (kind of solid surface, temperature of solid surface).

From findings 1 and 2 we conclude that:

Interaction phenomena between rarefied gases and solid surfaces are influenced by the kind of gas as well as by the type of solid surface.

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It follows from this that the internal friction $\mu$ as well as the external friction g and, therefore, also the coefficient of slip $\gamma$ /6

$$\gamma = \frac{\mu}{g} \tag{1}$$

depend on the kind of gas and the type of solid surface.

To form the coefficient of slip from the kinetic quantities, we derive the equation

$$\gamma = \frac{2}{3}\,\frac{2-C}{C}\,\lambda g \tag{2}$$

$\overline{\lambda g}$ = mean free path of the gas
c = a phenomenological quantity comprising the interaction between the gas and the solid surface
So far the quantity c is considered to be constant. The experiments mentioned above show however that c cannot be considered constant, but is a function of the molecular kinetic quantities of the gas as well as of the solid surface.
$\overline{\lambda g}$ = mean free path of a gas particle
m = mass of a gas particle

r = radius of a gas particle $(= f(\overline{\lambda_g}, m, \gamma, \overline{\gamma}, \overline{\lambda_w}, M, R, \overline{w}, P(d))$ (3)
$\nu$ = velocity of a gas particle
Tg = temperature of a gas particle
$\lambda w$ = distance between two particles of the solid surface

M = mass of a particle of the solid surface
R = radius of a particle of the solid surface
w = velocity of a particle of the solid surface
Tw = temperature of a particle of the solid surface

Viewing the simple kinetic mechanical interaction and, moreover, the interaction resulting from the action of atomic and molecular forces between the gas particles and the solid surface in the form of a potential:

$$P = f(d) \tag{4}$$

(d = the distance between a gas particle and the solid surface), we fundamentally obtain via equations (3) and (4) the physical interaction mechanism between a gas particle and a particle of the solid surface.

II. Any attempt at a physical interpretation of experimental forward deflection of molecular jets at solid surfaces leads to examination of the data of the observed reflection.

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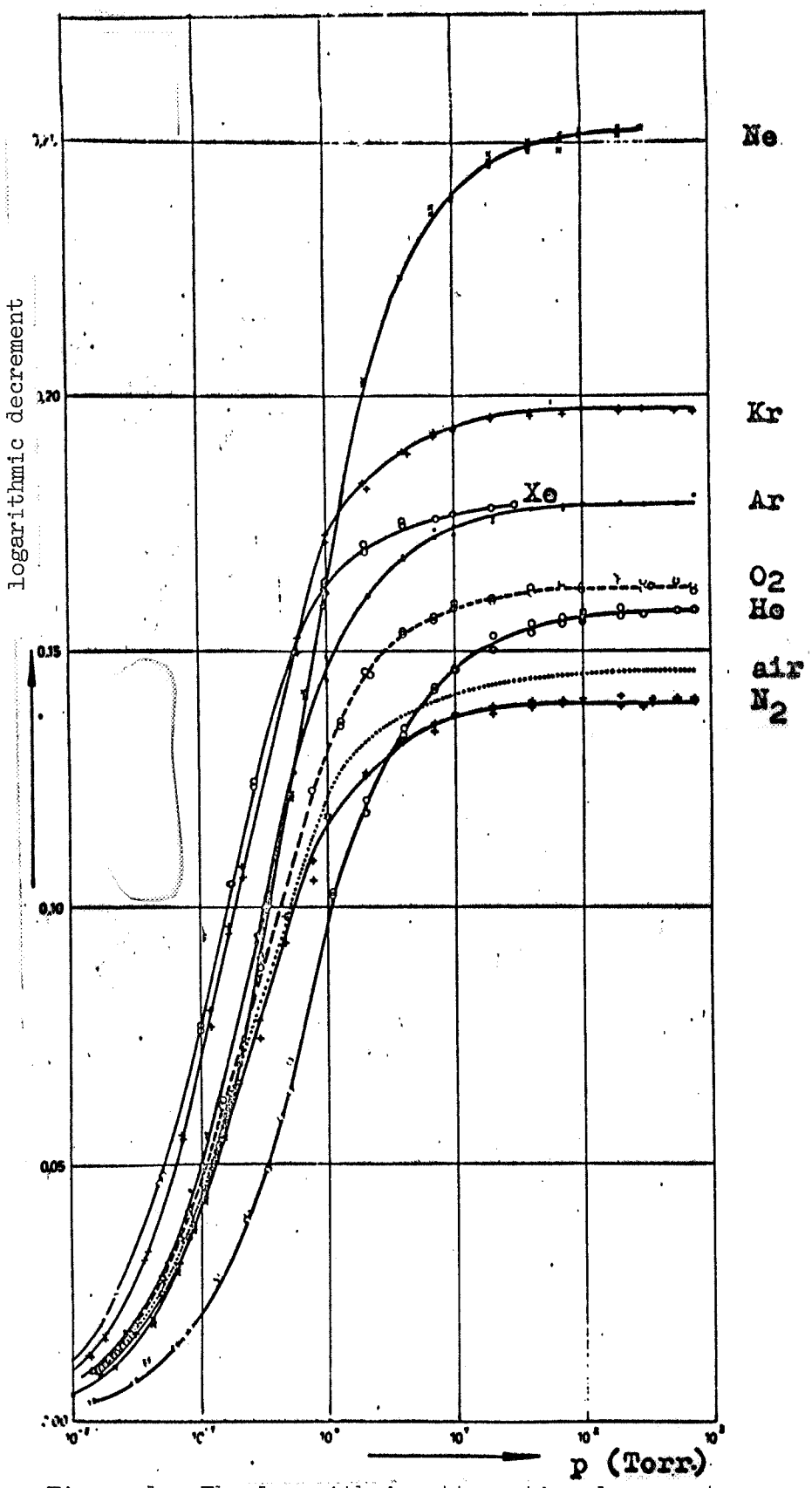



Figure 1. The logarithmic attenuation decrement as a function of gas pressure.

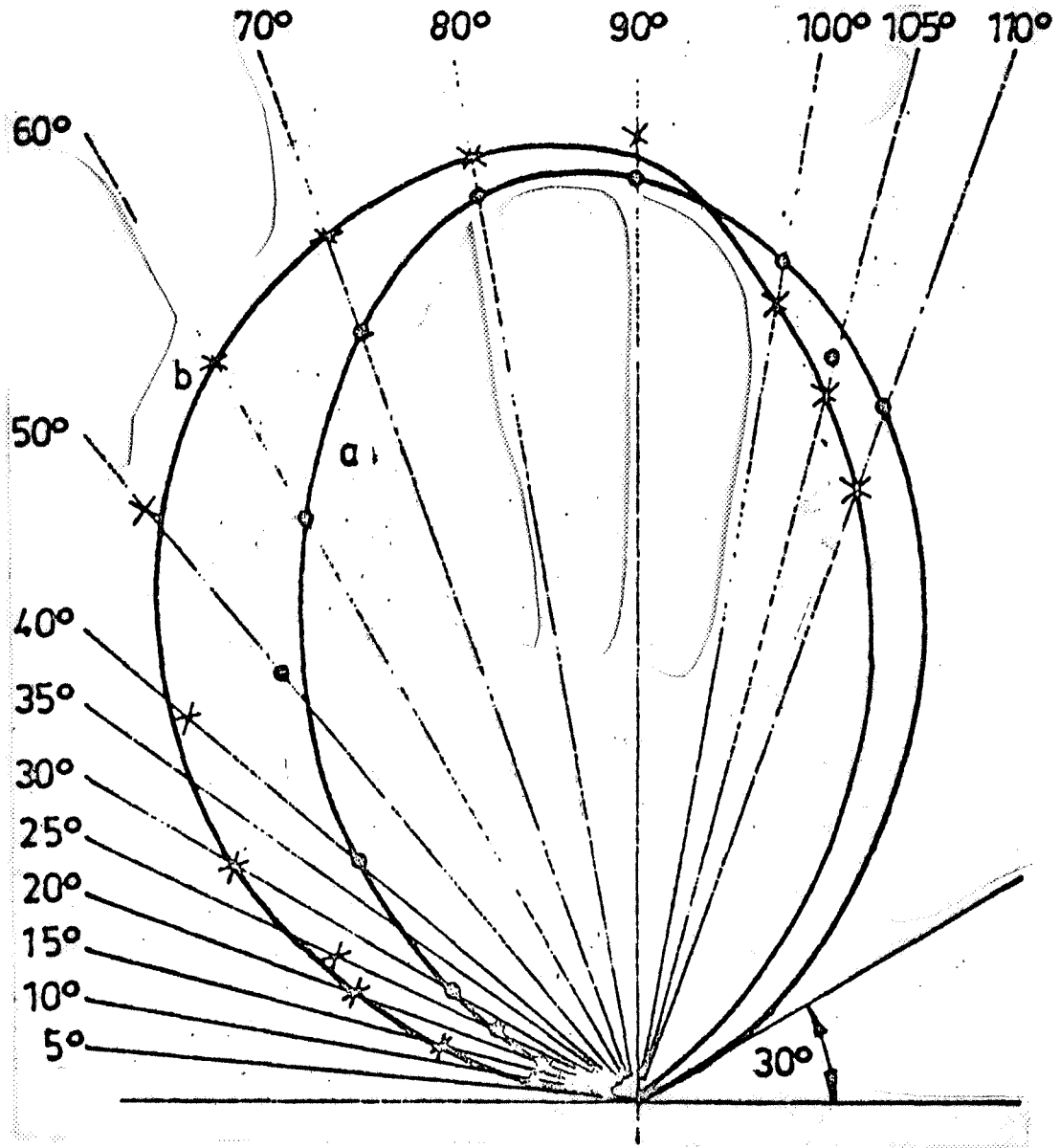



Figure 2a. Reflection of argon atoms (probe M21). The values of reflection intensity are given in polar coordinates in all directions. The angle of incidence of the primary molecular jet is 30°.

Curve a: metallic probe surface.
Curve b: dielectric surface.
Molecular jet pressure at the source: $1.9 \cdot 10^{-1}$ torr.

Pressure in receiver: $4.2 \cdot 10^{-6}$ torr.
Surface temperature: approx. 40°C.

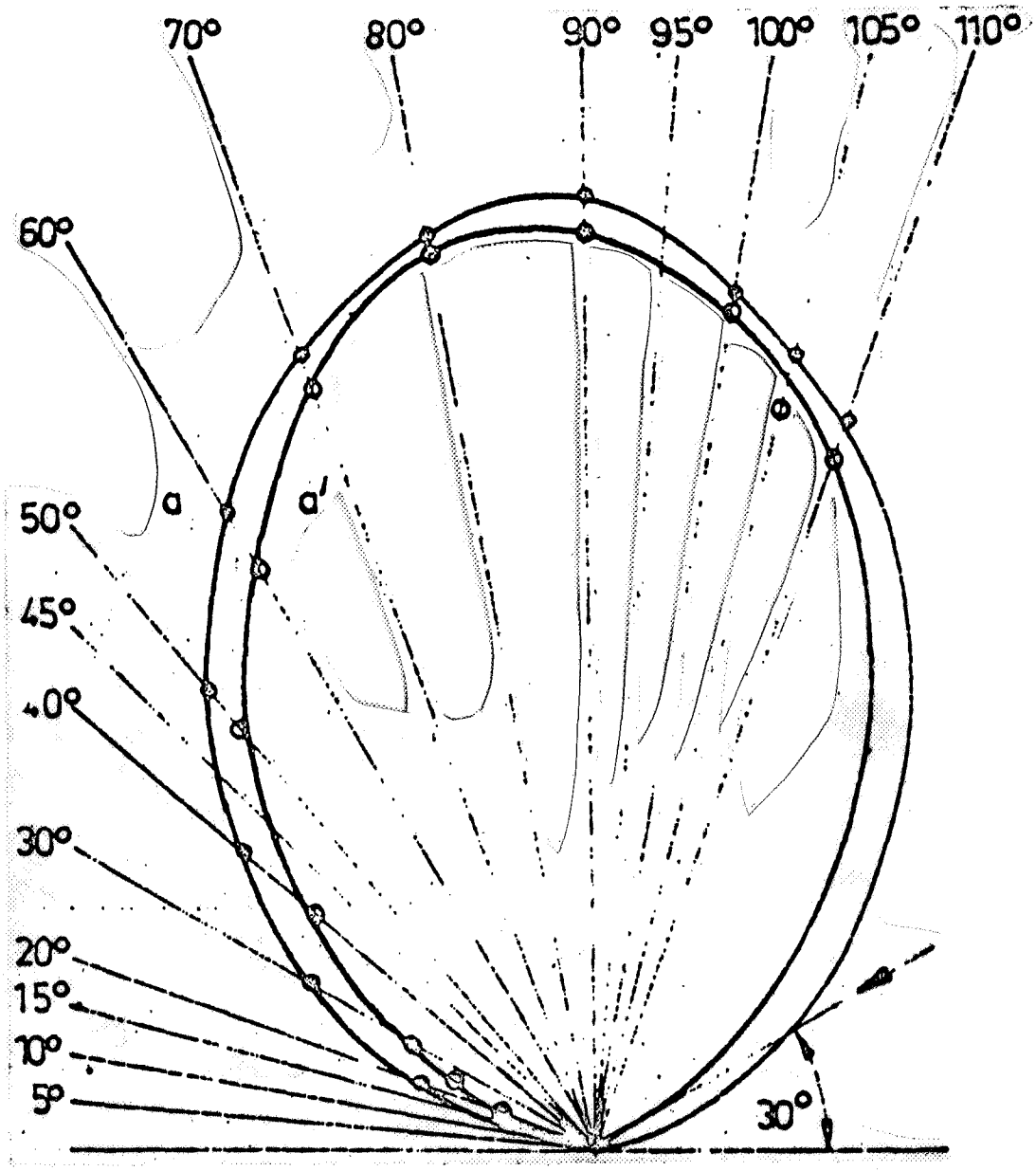



Figure 2b. Temperature dependence. Metallic-surface (silver) reflection of argon atoms (probe M21). The values of reflection intensity are given in polar coordinates in all directions. The angle of incidence of the primary molecular jet is 30°.

Curve a': surface temperature approx. 40°C.

Curve a: surface temperature 266°-283°C.

Pressure in receiver: $3.85 \cdot 10^{-6}$ to $4.2 \cdot 10^{-6}$ torr.

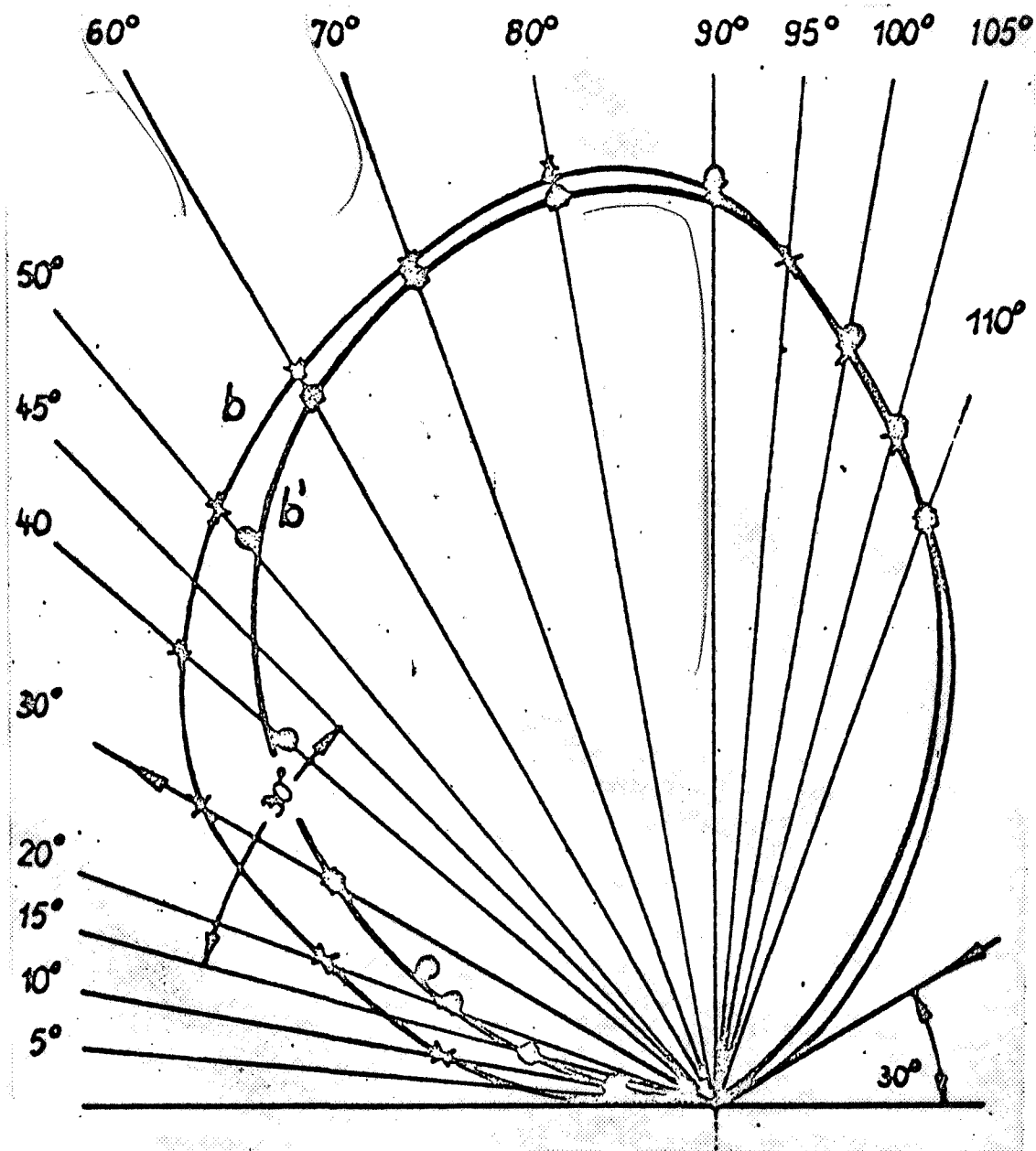



Figure 2b[1]. Temperature dependence. Dielectric-surface reflection of argon atoms (probe M21). The values of reflected intensity are given in polar coordinates in all directions. The angle of incidence of the primary molecular jet is 30°.
Curve b': surface temperature approx. 40°C.
Curve b: surface temperature 266°-283°C.

Pressure in receiver: $3.85 \cdot 10^{-6}$ to $4.2 \cdot 10^{-6}$ torr.

Analysis of the spatial distribution curves (Figures 2a, 2b) leads to the assumption of three different actions:

Imagining a spherical intensity distribution, we see from the experimental distribution curves:

(a) they are elongated along the axis of symmetry perpendicular to the solid surface; that is, they are deformed ellipsoidally;

(b) the eccentricity of the ellipse of intersection can be considered a measure of the deformation

$$\text{ratio of axes } e = {}^{b}/_{n} = c\ (T)$$

At the same time, we can consider a pronounced declination between the axis of symmetry and the axis perpendicular to the solid surface. This declination effect proves to be a function of the temperature of the solid surface Tw

$$\nu = \nu(T_w)$$

for a metallic solid surface as well as for a dielectric surface.

(c) the third observable effect is the appearance of the bends in the spatial distribution

$$\chi = \chi(T_w)$$

Examination of the Reflection Data

According to the physics of solid bodies, the interaction between a rarefied gas and a solid surface is understood to be an atomic interaction. The kinetic theory of matter treats this interaction as the occurrence of molecular collision between gas particles and solid surface particles. From this, we revert to the idea of a collision between a gas particle and a geometric surface in the sense of the continuum theory of solid bodies.

The solid surface is physically well defined by the introduction of a solid body of well-known lattice structure, that is, by the introduction of a lattice system having distance $\lambda_W$ between the elements of the lattice, element mass M, radius R and temperature Tw of the solid body, corresponding to the pronounced energy of the oscillating elements of the lattice.

To simplify the discussion, we make the following assumptions:

(1) the solid body is composed of atoms of a single kind, having mass M and radius R, and arranged in a cubic lattice having distance $\lambda w$ between the centers of the elements;

(2) specific thermal vibration is disregarded ($Tw = 0^{o}K$);

(3) an additional simplification is made by replacing the solid-surface particle of radius R and the gas particle of radius r by a sphere of action of radius = R + r and a flux of punctual particles;

(4) moreover, it is assumed that the mass of the gas particle $m \lesssim M$, the mass of a particle of the solid surface; that is, $m = 0$ approximately or m is negligible compared to M (true for the motion of metallic space vehicles at altitudes of 60 km, where hydrogen predominates in the atmosphere);

(5) the interaction between gas particles and the solid surface takes place by molecular collision with a definite radius of action;

(6) the velocity v of the gas particles is uniform.

Collision Between a Single Surface Particle and a Gas Flux

First, we assume a single sphere of action exposed to a flux of punctual particles of density N (number $cm^{-2}sec^{-1}$) incident in a direction perpendicular to the solid surface. Using the assumptions stated above, we obtain (law of optical reflection):

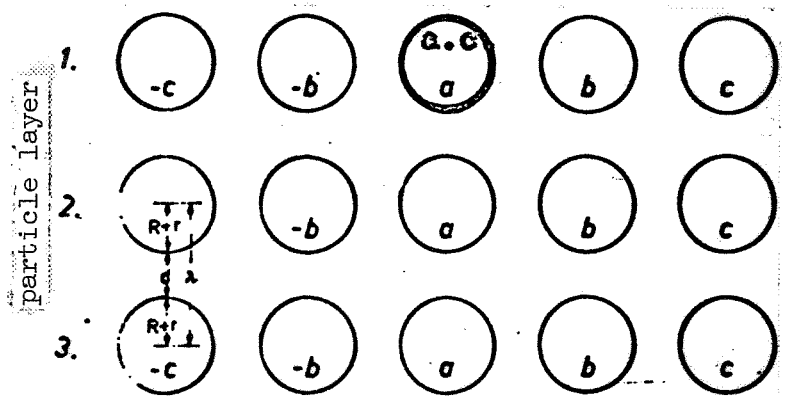
(1) retention of velocity v during collision

(2) the angle of deflection on the sphere of action is twice the angle $\beta$ between the direction perpendicular to the solid surface and the line connecting the center and the point of collision on the surface of the sphere of action.

The number of punctual particles dN of the gas incident on the element $d\Omega$ of the sphere of action is given by

$$dN = \frac{(R+r)^2}{2\pi} N \cos\beta \cos\varphi \, d\Omega \quad \text{or} \quad \frac{dN}{d\Omega} = N \frac{(R+r)^2}{2} \cos\beta \cos\varphi$$

Arrangement of the assumed spheres of action (radius R + r) for the principal section of a cubic lattice.




R = radius of surface particle
r = radius of gas particle
R + r = radius of the sphere of action
d = distance between the sphere of action
$\lambda$ = 2 (R + r) + d = lattice constant
a.c. = central atom

$$\delta = \frac{d}{R + r}$$

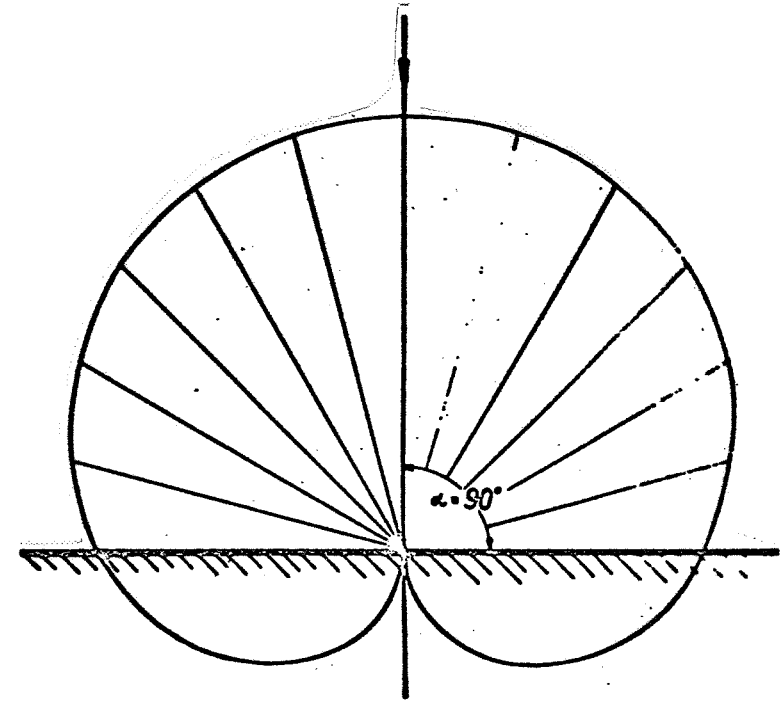



Figure 3. The intensity distribution of the rays reflected from a single surface particle gives a cardioid curve in the principal section. Angle of incidence $\alpha = 90^{\circ}$.

This number dN will be reflected at the angle $2\beta$. The energy flux of gas particles after collision is represented by the vector

$$\bar{J} = N\left(\frac{R+r}{2\pi}\right)^2 \cos\beta\cos\varphi \begin{Bmatrix} \cos 2\beta \\ \sin 2\beta \end{Bmatrix} \begin{Bmatrix} \cos 2\varphi \\ \sin 2\varphi \end{Bmatrix}$$

The distribution on a great circle of the sphere of action is given by a cardioid curve (the center section of the spatial distribution) (Figure 3).

In the general case where the angle of incidence $\alpha$ is between the direction perpendicular to the solid surface and the direction of incidence of the gaseous flux, the reflection of gas particles is given generally by spherical symmetry by turning the cardioid curve toward the direction of incidence.

The Action of Adjacent Particles on Spatial Distribution After Collision

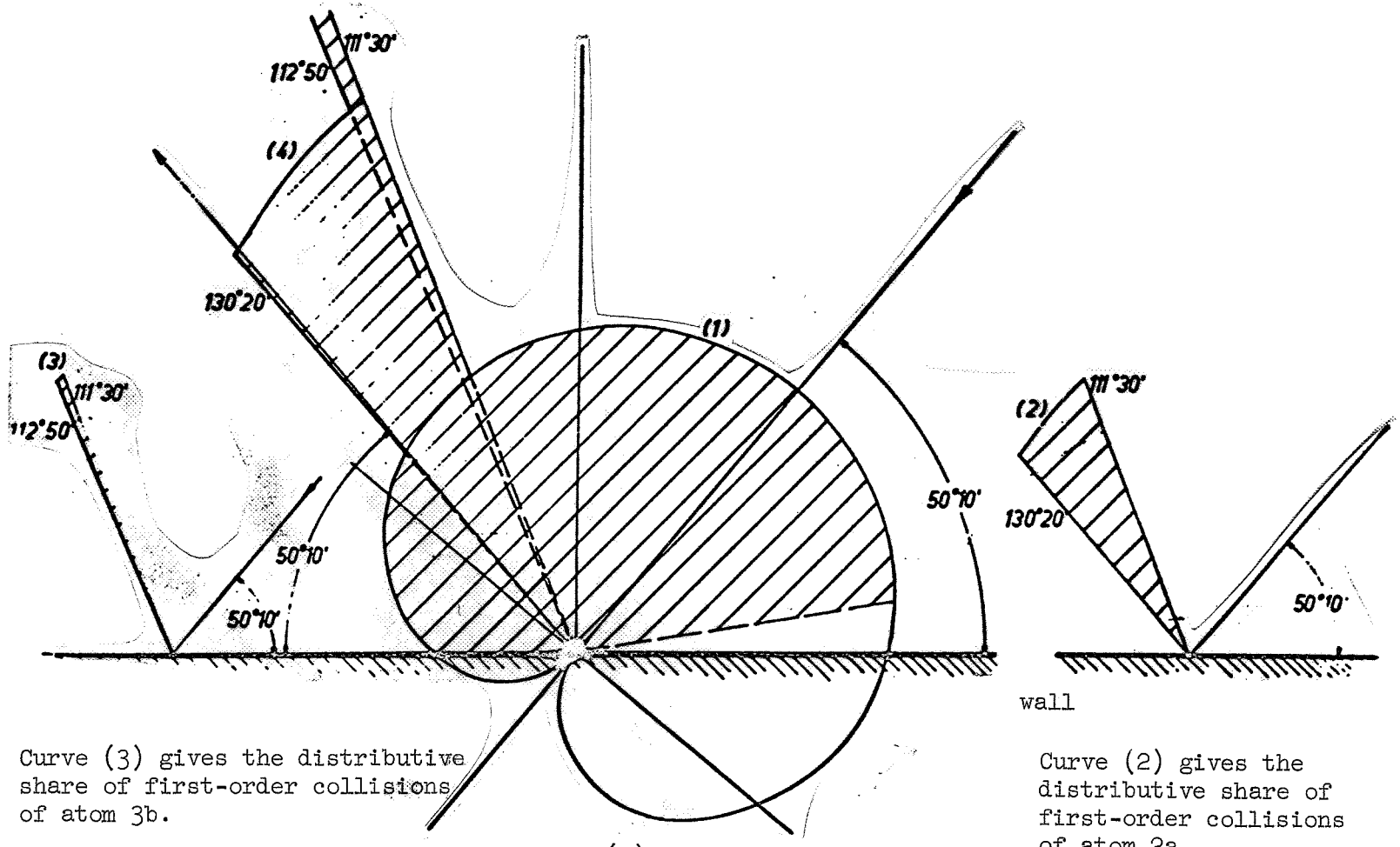
On an actual surface, the center particle is surrounded by several adjacent particles at distances determined by laws of the structure of solid bodies.

The closest neighboring particle prevents the complete development of postcollision distribution of particles by its screening action. We designate the path of a gas particle centrally incident to a particle of the solid surface in a direction perpendicular to the surface by (0). There is another path of a gas particle after collision that grazes the neighboring particle (1). The direction of (1) depends on the ratio R r of the distance between two adjacent particles and the radius of the sphere of action. The gas particles incident between the directions $(0) \leqslant x \leqslant (1)$ will be reflected into the gaseous space by a single collision. The flux of reflected particles is given by the above-mentioned cardioid curve within the limits (0) and (1).

There is another ray (2) designating the path of a gas particle that will be reflected the first time at the surface of the central particle, a second time at the surface of the particle adjacent to the center particle, and that grazes the center particle after the second collision. Gaseous particles incident between the directions $(1) \leqslant r \leqslant (2)$ will be reflected into the gaseous space after two collisions. Their distribution is superimposed only once on the spatial distribution (cardioid curve) of the particles reflected.

This is valid for each immediately adjacent particle. Their number depends on the structure of the first layer of the solid surface.

Figure 4. Polar diagram of the intensity distribution when $\delta = 2$, angle of incidence $50^{\circ}10'$.




Curve (3) gives the distributive share of first-order collisions of atom 3b.

Curve (1) gives the distribution around atom 1a. Curve (4) represents the superposition of curves (1), (2), and (3).

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Curve (2) gives the distributive share of first-order collisions of atom 2a.

A certain number of gas particles reflected once at the surface of the central particle strike not only particles of the first layer but also those of deeper layers. Only a fraction of these particles will be reflected into the gaseous space and thereby change the spatial distribution of particles reflected at the first layer of the solid surface (Figure 4).

Let us consider gas particles passing through the space between two adjacent particles of the first layer. They strike some particles of the second, of the third and of lower layers. A certain number of particles are reflected into the gaseous space by a single collision withing the upper layers of the solid body. They contribute a further modification to the spatial distribution of gas particles reflected once at the first layer of the solid body.

Collisions of higher order (3, 4, and so on) influence the spatial distribution of gas particles after collision to a degree that decreases rapidly with the order of collision.

The distribution function for gas particles after collision consists of the superposition of similar individual functions of the particles of the solid body. Each particle of the solid surface may be considered a central particle, including the contribution:

1. from first-order collisions with particles at lower levels near the central particle. This contribution is greater than the influence of higher-order collisions (Figure 5);

2. from higher-order collisions with adjacent particles of the first and lower layers.

The total number of particles of the solid surface is defined:

(1) by the lattice structure;

(2) by the lattice space.

In the case of a cubic structure the surface density of particles in the solid surface is given by:

$$\frac{N}{W} = \frac{1}{\lambda_w^3}$$

The individual distribution functions of all these particles are superimposed upon each other.

The described conditions of reflection are approximately exact for the case of a solid body at rest with respect to the gas.

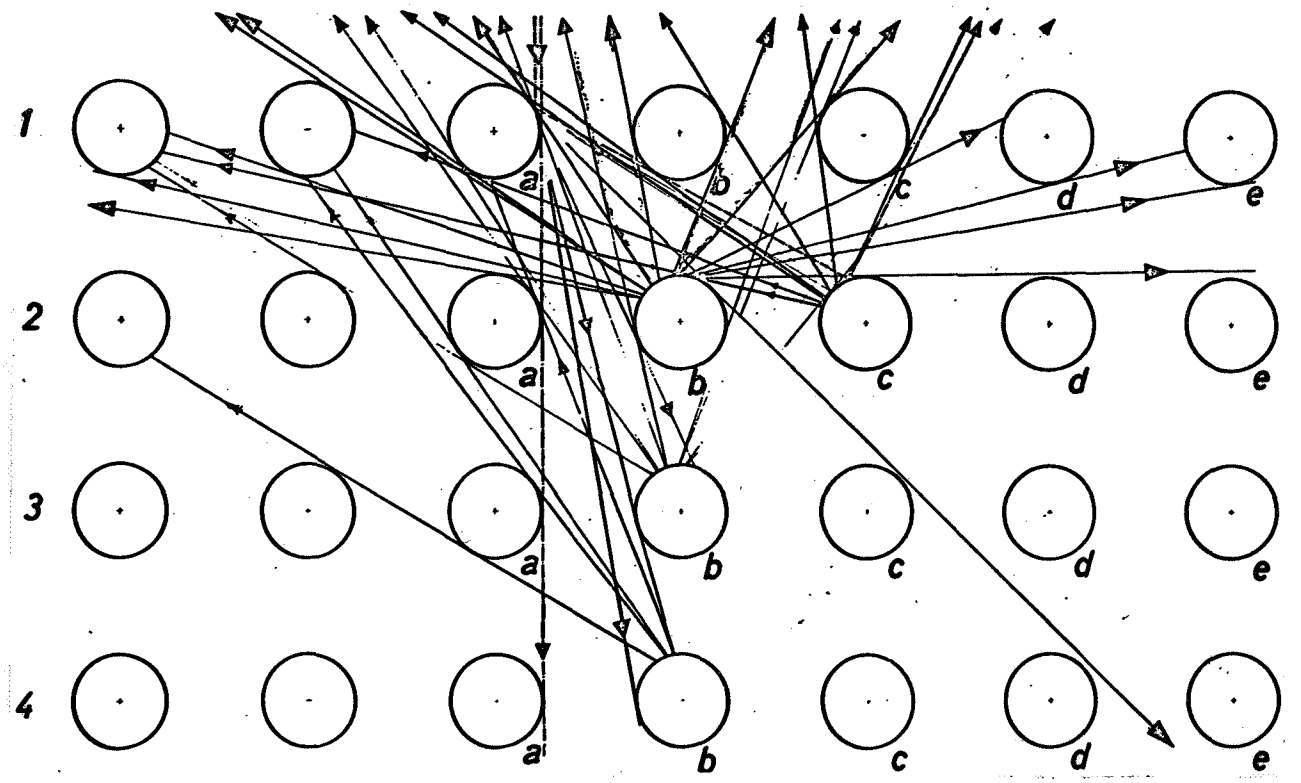


Figure 5. Second-order collisions between gas particles and particles of the 2nd, 3rd, etc., layers of the solid body.

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The motion of a space vehicle can be defined by introducing the velocity W of the uniform rectilinear motion of the solid body.

The spatial energy distribution of the gas particles after collision will be deformed in the manner shown in Figure 6. The cardioid curve is deformed by the normal velocity of the solid body. Energy transfer will increase in proportion to the ratio of the specific velocity of the space vehicle to the mean velocity of the gas particles.

This paper has treated only the special case:

$$c(m = 0,\ v = \text{const},\ r,\ \lambda_g,\ M,\ R,\ \lambda_W\ W \sim T_W = 0)$$

$$P(d) = 0$$

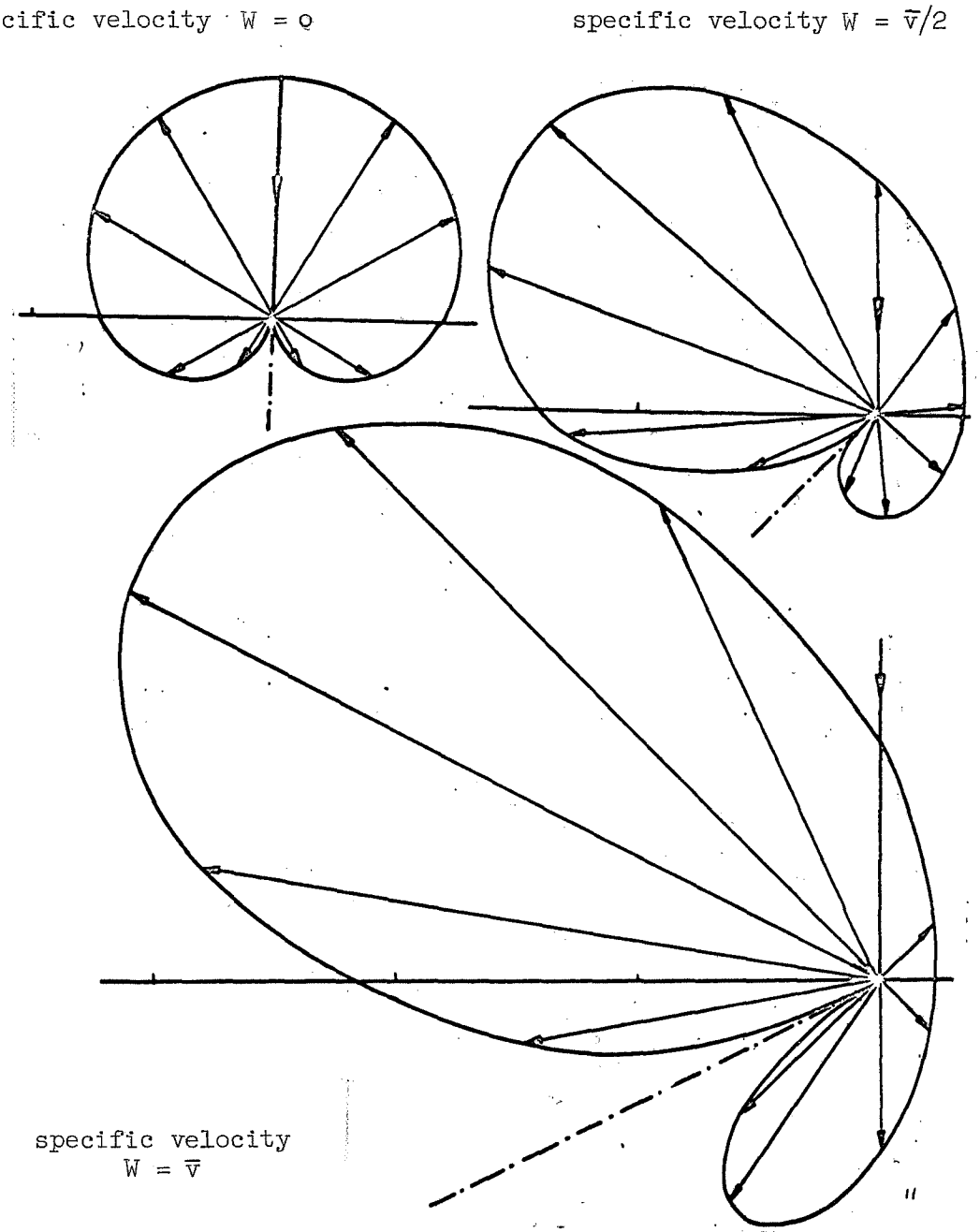


Figure 6. Spatial distribution of energy flux of gas particles after collision. Specific motion of solid surface. Special case m = 0.

It is generally necessary to consider these parameters which have been hitherto disregarded.

The report of M. Mader discusses the following subject:

$$m \neq 0,\ T_W \neq 0,\ P(d) = 0$$

We see then an important influence between:

the temperature of the gas and of the solid body respectively,

the ratio of the masses of the gas and a particle of the solid body,

and the spatial energy distribution of the gas particles after collision.

M. Weidner's report will discuss the influence of mutual potential energy between a gas particle and a particle of the solid surface on spatial distribution after collision.

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